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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY.

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Introduction.

The curious phenomenon of the residual charge which appears after a discharge by a momentary short circuit in a condenser which has a solid dielectric was observed as early as 1768 by Franklin, in the case of a glass "Franklin's plate"; but systematic research into the laws governing the formation and liberation of residual charge did not begin until about 1854, when R. Kohlrausch published the first important article on the subject. Up to that date it was the common belief that electric charge actually penetrated from the armatures of a charged condenser into the dielectric substance, from which it slowly returned to the armatures after each momentary discharge. The results of Kohlrausch showed, however, when viewed in the light of the theory of electric potential, that the penetration hypothesis was unsound, and that the true explanation was to be looked for in a polarized state of the molecules in the dielectric, in accordance with Maxwell's theory. Kohlrausch laid down the following two fundamental laws governing residual charge formation:

1. *The actual charge which can be drawn instantaneously from a charged condenser is at all times proportional to the potential difference of the condenser terminals.*

2. *In the same condenser the residual charges formed during equal times after charging are proportional to the initial charges, or the charging potentials.*

If the penetration hypothesis were correct, then during a momentary short circuit of a charged condenser charges of opposite sign should flow on to the condenser armatures in order to neutralize the potential of the charges which penetrated a short distance into the dielectric; while according to Kohlrausch's views the polarization of the molecules in the dielectric has the effect of neutralizing the potentials

of a part of the initial charge, "binding" it, as it were, so that it cannot take part in the discharge, and only becomes free gradually as the polarization decays. A simple but crucial test as to which theory must certainly be wrong is therefore to remove the armature plates of a condenser immediately after an instantaneous discharge and test the sign of their charges. This was done by Wüllner, and the results conclusively disproved the older theory.

Wüllner observed the decreasing potential of charged condensers made of the same kind of glass but of varying thicknesses, and the results established a third law, which had been overlooked by Kohlrausch :

3. *In condensers of the same dielectric but of different thicknesses and shape the rate of fall of potential after equal times is the same.*

Still another law, of great importance, seems to have been first discovered by Thomson, and may be stated thus :

4. *Residual charges come out of a condenser in the inverse order to that in which they went in. Or, the rate of decay of residual charge during a long-continued short circuit is the same as its rate of formation during a long-continued charging.*

The second and third laws are ordinarily put together into a single one, called the law of superposition. The first three may be generalized and briefly put into mathematical form :

For condensers made of the same dielectric, the following equations hold, provided we neglect losses to the air and those due to internal conductivity:

$$V_t = V_0 \cdot f(t) \qquad Q_t = Q_0 \cdot f(t) \qquad R_t = Q_0 - Q_t;$$

where V_0 = charging potential,
V_t = potential t seconds after charging,
Q_0 = initial instantaneous charge,
Q_t = charge which may be drawn from condenser in an instantaneous short circuit after t seconds of insulation,
R_t = residual charge formed after t seconds of insulation.

Thus the function $f(t)$ is one which is characteristic of any given kind of dielectric, as paraffin or mica.

Later researches have in general confirmed the law just given, but have not added any others, unless we are willing to accept Hopkinson's generalization of the law of superposition to include with instantaneous forces forces acting at different times, and this has hardly been conclusively proved.

The theories attempting to account for the cause of formation of residual charges have in the main followed one of two fundamentally

different lines of thought. One holds that the heterogeneity of the dielectric is the cause of residual charge, and this theory has been developed by Maxwell and Rowland. The second ascribes the greatest importance to the elastic properties of the dielectric in the formation of residual charges. Hopkinson developed a theory of residual charge analogous to Boltzmann's theory of elastic after-effects, but this is too general to be of practical use. Of the many other later theories which take account of the elasticity of the dielectric, the one formulated by Houllevigue [1] seems to be the most promising. He gets a fairly simple solution of his differential equation for the current flowing into a condenser during a continuous charging. This current is made up by superposing the ordinary, practically instantaneous, charging current upon the slower residual forming current, which lasts for an appreciable interval of time. This latter current is considered to be due to a slow displacement of a part of the ether, being conditioned by the molecules of the dielectric.

In recent years the questions of "viscous dielectric hysteresis" or "lagging polarization," and of "energy losses" in the dielectric, have claimed much attention among physicists, and for a considerable time the problem of residual charge was completely overshadowed by these later questions. Some energy is undoubtedly lost in the form of heat in the dielectric, when the electric force is continually varied, as in an alternating current or a rotating electrostatic field. It is still an open question whether this loss of energy is chiefly to be associated with Joulean heat production in the dielectric, or with a viscous lag of the dielectric polarization behind the polarizing force. Each side of the question has found numerous and able supporters. It is greatly to be desired that a conclusive answer be obtained as soon as possible, for the subject is not only of immense practical importance in all telegraphy, telephony, and electrical engineering practice, but has undoubtedly very close relations to the problem of the ultimate constitution of matter. In fact the question of dielectric viscosity, or energy losses in dielectrics, seems to be an important part of electric dispersion, a subject which is just now receiving considerable attention.

The latest development of these very interesting questions of dielectric viscosity and energy losses seems to be a reopening of the older problem of residual charge formation. Indeed some of the most recent writers on the subject, especially E. R. von Schweidler,[2] appar-

[1] Ann. de l'Univ. de Lyons, **32** (1897); J. de Phys., **6**, 113–120, 120–126 (1897).

[2] Ann. der Phys., **24**, 711 (1907). This paper gives an excellent bibliography of the subject.

ently consider that both "viscous hysteresis" and "energy losses" are nothing more than results of the older phenomenon of residual charge formation, and are most satisfactorily explained in terms of it. Residual charge had been considered to be only a slow after effect of dielectric polarization, and almost every one who dealt with the subject tacitly assumed that the residual forming current is negligibly small during the charging of the condenser, so that no residual charge worth mentioning forms, say, in one thousandth, or even one hundredth, of a second after the charging voltage is applied. This assumption explains why nearly all investigators of residual charge, except some of very recent years, thought it unnecessary to make their charging times and short-circuit times extremely short, or even to measure or to estimate them. Even the wording of the "laws" which have been stated is very indefinite, as they speak of "instantaneous charges" and "instantaneous short circuits" if they attempt to define these time-intervals at all.

The present research started out with an attempt to test for the presence of an appreciable lag of polarization in paraffin paper condensers. The effect observed was, however, found to be due to a residual charge formation occurring in less than one tenth of a second, and I was led to an extensive investigation of the rate of residual charge formation at times as near to the instant of beginning the charging of a condenser as it was possible to obtain with the apparatus employed.

Neglecting for the moment various results of secondary importance, I wish to describe in detail in this paper three things which I hope will prove to be of some interest and value as contributions to the scientific study of dielectrics:

First, a method of studying the rate of formation of residual charge during very short charging intervals. This is a differential, or second order, method, and is capable of a very high degree of accuracy. Its great advantage is that it measures *all* the residual charge formed, no charge being lost in the process of short-circuiting the condenser.

Secondly, the best results of many observations on various dielectrics embodied in a series of curves, which although only first approximations, give correctly the general character and magnitude of the residual forming current for the time interval 0.00007 to 0.00170 of a second during which the charging voltage has been applied. These results show that the residual charge formed in this very short time is considerable in condensers made of paraffined paper and glass, and appreciable even in mica condensers.

Thirdly, a process for preparing with the greatest ease sheets of pure paraffin of almost any desired thinness, to be used in building up

condensers of considerable capacity. Three condensers thus built up showed practically no residual charge, even when tested by the sensitive method used in this investigation.

Preliminary Experiments with Electrostatic Voltage Cycles.

The results of some experiments conducted in the fall of 1907 with the view of testing for a possible lag of polarization were of value to the writer only because they led him to investigate the rate of formation of residual charge for very short times after the charging. However, a brief description of the method employed may not be without some interest.

By means of two wooden arms, which swept contact brushes over two rows of copper plugs connected to sections of a storage battery of fairly high voltage (say 800), two condensers of very nearly equal capacities were simultaneously charged to the same final potential, then by an electromagnetic device immediately discharged against each other, and the charge left over was then sent through a ballistic galvanometer and measured. In this process both condensers were charged by increasing the voltage by steps of 30 or 60 volts, but one was charged to the final voltage by stopping its arm over any desired plug, while the other was charged up to say 420 volts, then decreased by steps until the voltage was again equal to that of the first condenser. I thought that the polarization corresponding to the highest voltage might not have time to decay before the two condensers were connected together. The wooden arms were flung over the copper plugs by hand, however, so that the time interval of decreasing the potential of one condenser was of the order of 1/20 second. This is probably too long a time for a perceptible lag effect to continue; the throws obtained were, however, considerable. But the charges behaved in every way just like residual charges, taking an appreciable time to come out of the condenser, although they had been formed in a very short time.

The principle of the method of mixtures which was here used was carried over into the later work with great advantage. In these new experiments the condenser to be tested was opposed to a standard air condenser, in which no residual charge formation was supposed to occur. Thus comparisons were rendered simple, as no variable effects due to one condenser had to be eliminated.

Description of Apparatus used in Later Experiments.

The Storage Battery.

The storage battery which charged my condensers is of the same type as the large 40,000 volt battery used by Professor Trowbridge for discharge experiments in tubes of high vacua, although it has a total voltage of only about 900 volts. The cells are test-tubes with lead strips dipping in a sulphuric acid solution; they are placed in racks of paraffined whitewood, each rack holding two rows of 30 cells each. Such a storage battery cannot yield large steady currents for any considerable time, but for furnishing a constant electromotive force and for charging condensers it is extremely useful. An hour or two of charging the battery early in the morning is usually sufficient to give it a fairly constant voltage for the whole day.

The Air Condenser.

The preliminary experiments briefly described above, although quantitatively almost worthless, showed clearly two things: first, that residual charges can form in considerable amounts in a very short time interval, say in a tenth of a second; and, secondly, that if the neutralizing two-condenser method was to yield the best results, in fact if it was to yield results of any quantitative value at all, it would be necessary to construct a standard condenser which should be free from residual charge formation, or which should show this effect only to a negligible degree. I therefore decided to build an air condenser of such capacity that its charge might give ballistic throws of large amplitudes, so that the "difference effect," when used against a test condenser in the manner already described, might still be of measurable magnitude. An air condenser was desirable because gaseous dielectrics, if they form residual charges at all, do so only in exceedingly minute quantities.

I selected, therefore, twelve large sheets of very flat plate-glass from the stock of the Boston Plate and Window Glass Co. in South Boston. Of these, seven were of dimensions 63.5 by 66 cms., and the other five were 61 by 66 cms. Their thicknesses varied considerably, being from 0.8 to 1.0 cm., but this did not make any difference for my purpose. The plates were carefully cleaned, and then on both sides of each plate tinfoil sheets were pasted with Higgins' Photo-Mounter paste considerably softened with water. It was found that the best results could be got when a squeegee roller, continually dipped in water, was used to roll out the tinfoil sheets and to force out all the surplus

pasty liquid from under the tinfoil. Care had to be exercised in order not to tear the tinfoil, which was very thin, — about 0.004 of a centimeter. It was bought in the form of a continuous roll, 30.5 cms. in width; thus only two sheets were necessary to cover each side of a plate, a free margin of about 4.5 cms. being left around three edges, while the tinfoil itself projected over the fourth edge about 1 cm. The reason for using the paste instead of shellac was that paste is a conducting material, and thin films of it, which might possibly be left over the tinfoil, would not cause any residual charge, while if the dielectric shellac had been used, these thin films might perhaps have given rise to small but troublesome residual charges, which were especially to be avoided. The tinfoils on the two sides of a plate projected over the same edge of the plate, and were pressed down with thicker paste over a fine strip of copper foil all along this edge. The copper wire terminals of the condenser were soldered on to these strips with wax flux.

To separate the tinfoil-coated glass plates, which must be done by some very good insulator, it was decided to use thin glass disks, provided they could be found of the proper thickness, rather than disks of hard rubber, because this latter substance changes its surface condition in time. Fortunately a pane of glass was found of just the desired thickness, 0.076 cm., and a great number of disks 1.1 cms. in diameter were cut out of it and ground smooth at their edges.

Ten of these were placed between every two successive plates of glass, seven around the marginal space, and only three in the tinfoiled region. For these three circular pieces of tinfoil, 2.5 cms. in diameter were removed, and the paste below them carefully cleaned off. The disks were pressed down onto the glass plate with a very small drop of liquid shellac in between. Small weights were then placed on top for a day or two, so that the shellac might have time to harden under pressure. Then, for the sake of better insulation, a little melted paraffin was guided around the under edge of each glass disk with a hot iron wire.

In the air condenser built up of these plates there were eleven layers of air, each about three quarters of a millimeter thick. This condenser, which was mounted in a large oak case made for the purpose, has a capacity of 0.0428 microfarads and an insulation resistance of 35,000 megohms.

The Falling Weight Machine.

In studying the rate of formation of residual charges for very short charging intervals, Professor B. O. Peirce's large falling weight machine was found to be of the greatest use. A massive oak frame 244 centi-

meters high inside, 45 centimeters wide, and 22 centimeters deep (Figure 1), serves to support three vertical rods or columns made of straight round steel shafting 3.8 centimeters in diameter held at top and bottom in iron castings. On the middle column slides smoothly a cylindrical iron weight **Q** which can be caught and held at any convenient height by a latch **K** which can be slipped from a distance by a string. The weight as it falls can be made to trip in succession a number of switches supported on the other columns, and thus to open or close a a series of circuits at definite intervals. A dash pot **N** at the bottom of the middle column catches the falling weight.

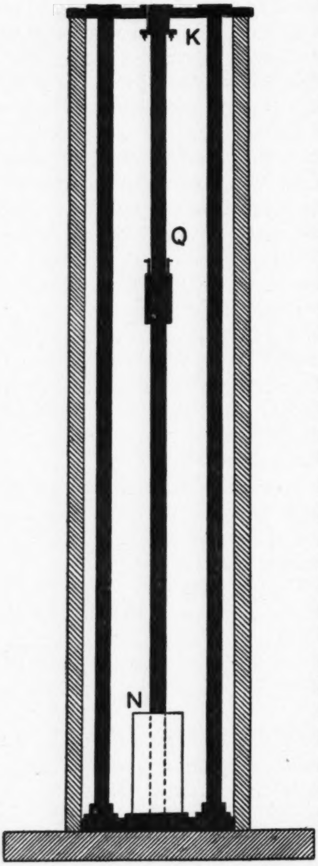

FIGURE 1.

In the early experiments made with this apparatus the falling weight was used to close in succession three keys. The first completed the charging circuit so that both condensers were charged to the same potential, usually 64 volts, the second discharged the condensers against each other, and the third put both condensers, still opposed, in circuit with a d'Arsonval galvanometer. For most of the work, however, the falling weight was equipped with six knife edges at the ends of short horizontal steel rods projecting, two towards the north, two towards the south, and two towards the front (east) of the apparatus. The last pair were insulated from the iron. These knives ploughed furrows in type metal pieces held in elaborate brass clamps mounted on the outer columns of the machine, but the south furrows were less than a millimeter long, while the east and the north furrows were 19 millimeters and 22 millimeters long respectively.

The Condensers used in the Tests.

Of the many condensers used in the work here described, some were built up of tinfoil and sheets of the best linen ledger paper saturated with paraffin wax of high grade. These were about twelve centimeters long and six and a half centimeters wide. After the paper had been soaked in the wax, the paper and tinfoil were built up into a pile and ironed together with a small flatiron moderately hot; the pile was then clamped permanently in large malleable iron holders made for the purpose. In the cases of two condensers, known as "Par. KA" and "Par. KB," the flatiron was not used. In "Par. B" and "Par. C" the paper was saturated with paraffin at a temperature near that of boiling water. In "Par. A," "Par. AA," "Par. BB," and "Par. CC" the paraffin was very hot, and the paper was kept in it until all the air bubbles in the paper had apparently been expelled. "Mica A_0" and "Mica B_0" were built up at room temperatures of tinfoil and single sheets of mica: after these condensers had been baked and waxed over to keep moisture out they were known as "Mica A" and "Mica B." Besides these a glass condenser, and three to be described later on in which the dielectric was clean, thin paraffin sheets were used.

Early Experiments with the Falling Weight Machine.

In these experiments, as has been said above, the falling weight first closed a switch which caused the two condensers to be charged to the same potential of 64 volts, then the relay broke the charging circuits and discharged the condensers against each other, and finally the last switch discharged the compound condenser through a galvanometer of such sensitiveness that the air condenser charged to 1 volt caused a throw of 0.732 centimeters. The sliding weight always dropped through a distance of 57.7 centimeters before it closed the first key, and a total distance of 130 centimeters before it closed the last key. The relay key could be set at any convenient height on its column, but if raised too high there would be no charging of the condensers. Experiment of this kind showed that there was a time lag of 0.0212 seconds in the relay circuit, and this had to be allowed for in all the computation. The voltage of the battery was determined by a Weston voltmeter.

When the relay key was placed as high as it could be without preventing the charging of the condensers, the fall of the weight caused a small throw of the galvanometer coil. This throw was due, just as it would be even if the time interval of charging were longer, to two factors:

first, the difference in the capacities of the air condenser and the test condenser; and, second, to the residual charge which had time to form during the charging interval. The test condensers "Mica A_0," "Mica B_0," and "Par. A" were adjusted to give very small throws when the charging interval was thus cut down as far as possible. But it is important to notice that this small throw does not necessarily measure the difference in the capacities of the condensers. For although the charging interval is indeed small, yet if it were reduced still further,

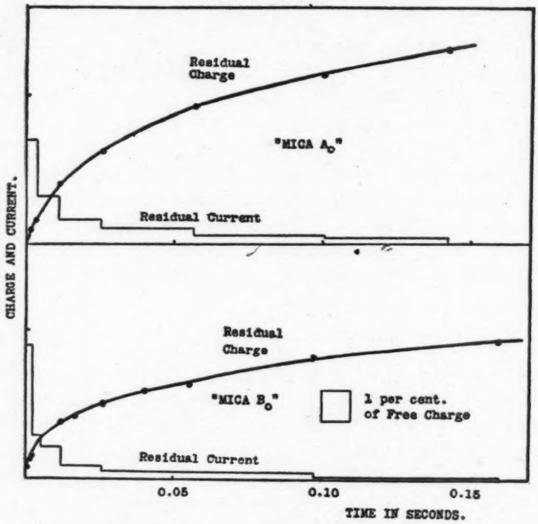

FIGURE 2. (Tables I and II.)

the air condenser might gain in apparent capacity on the test condenser, and the small throw, after perhaps first passing through the zero value, if it was at first in favor of the test condenser, might finally increase and keep on increasing. In other words, it is only when the small throw is in favor of the air condenser, that is, in the direction in which a throw coming from the air condenser by itself would read, that we can assert that the capacity of the air condenser is greater than that of the test condenser, for if the throw is in favor of the test condenser, we do not know whether the residual charge formed is less, equal to, or greater than, this charge causing the small throw. In fact, we see

that there may be considerable difficulty in defining the so-called "free charge capacity" of the test condenser. It seems to me that this term can only be safely used when it can clearly be shown that the charge from a condenser, with constant charging voltage, approaches a definite

TABLE I. (Figure 2.)

"Mica B_0" *vs.* Air.

V = 64 volts. Total Throw = 46.5 cms.

Charging Time in Seconds.	Ballistic Throw in Centimeters.	Throw expressed in Percentage of Total Throw (corrected).
0	−0.11	0
0.0006	−0.28	0.36
0.0016	−0.42	0.66
0.0022	−0.47	0.76
0.0053	−0.68	1.20
0.0124	−1.03	2.00
0.0170	−1.10	2.10
0.0121	−1.01	1.90
0.0265	−1.30	2.50
0.0410	−1.52	3.00
0.0560	−1.61	3.20
0.0980	−2.06	4.20
0.1600	−2.30	4.70
(4 min.)	−4.13	8.60
(23 min.)	−4.23	8.80

limit as the charging time is continually decreased toward zero, or, rather, as close to zero as the conditions for complete charging will allow. Considerable light will be thrown on this question, I hope, by the later experiments in this work. For the purpose of constructing Tables I, II, and III and the curves of Figure 2 the simplifying assumption is in general made in this work that *no residual charge is formed*

in the shortest charging interval secured in the experiment. In other words, we shall assume that the small throws obtained after this shortest charging interval are due *wholly* to the difference in "free charge capacity" of the two condensers. After all, since we find it so difficult to know the actual amount of the residual charge, we must temporarily content ourselves with the *differences* in residual charge

TABLE II. (Figure 2.)

"Mica A_0" *vs.* AIR.

V = 64 volts. Total Throw = 46.5 cms.

Charging Time in Seconds.	Ballistic Throw in Centimeters.	Throw expressed in Percentage of Total Throw (corrected).
0.1600	−3.50	6.90
0+	−0.27	0
0.0013	−0.47	0.42
0.0038	−0.62	0.74
0.0115	−1.18	1.90
0.0260	−1.70	3.00
0.0570	−2.41	4.60
0.1010	−2.90	5.60
0.1430	−3.30	6.50
1.0000	−6.70	13.70
(1 min.)	−8.50	17.60
(12 min.)	−8.50	17.60

formed for varying charging intervals. When ballistic throws are in favor of the air condenser, they will be regarded as positive; when the test condenser's charge prevails, we shall record the throws as negative. With these explanations we may now tabulate the results. (Tables I, II, III.)

If the principle of superposition, or in this case the simple proportionality of residual charge to the electromotive force applied to the condenser, held true for the range of potential used in this experiment,

then the numbers in the last columns should be constant for each charging interval. This is not true, however, for the higher voltages

TABLE III.

"Mica A_0" *vs.* Air Condenser.

Total Throw = V. (0.73).

Charging Time in Seconds.	Charging Voltage.	Ballistic Throw.	Actual Throw expressed in Percentage of Total Throw.
0+	128	− 0.80	0.86
"	64	− 0.47	1.00
"	192	− 1.22	0.87
"	256	− 1.82	1.00
0.0044	256	− 3.92	2.11
"	192	− 2.78	1.99
"	128	− 1.78	1.91
"	64	− 0.88	1.88
"	32	− 0.38	1.63
0.0155	32	− 0.70	3.00
"	64	− 1.52	3.25
"	128	− 3.30	3.54
"	192	− 5.30	3.78
"	256	− 7.40	3.98
"	318	−10.30	4.50
"	383	−13.22	4.80
0.0740	318	−19.60	8.40
"	256	−14.60	7.90
"	192	−10.43	7.50
"	128	− 6.58	7.00
"	64	− 3.00	6.40
"	32	− 1.42	6.10
0.1430	32	− 1.80	7.70
"	64	− 3.82	8.20
"	128	− 8.30	8.90
"	192	−13.3	9.50
"	256	−18.70	10.00
"	318	−25.00	10.70

show a much greater percentage of residual formation than the lower ones, as will be seen from the data of Table III.

The residual throws from the condenser "Par. A" are expressed in Table IV, for purposes of comparison, in terms of the total throw which the charging voltage would have caused in the air condenser.

TABLE IV.

"PAR. A." *vs.* AIR.

Volts.	Throw in Cms.	Time of Charge.	Percentage of Residual.	Volts.	Throw in Cms.	Time of Charge.	Percentage of Residual.
34	0.6	0+	2.4	452	5.38	0.145	2.06
66	1.2	"	2.5	388	4.70	"	2.10
131	2.4	"	2.5	324	3.90	"	2.09
196	3.85	"	2.72	259	3.12	"	2.08
262	5.2	"	2.71	194	2.34	"	2.09
327	6.6	"	2.76	129	1.57	"	2.11
393	7.9	"	2.74	66	0.78	"	2.05
196	3.95	"	2.75	33	0.39	"	2.06
33	0.6	0.0062	2.48	332	0.19	5 sec.	1.02
66	1.2	"	2.47	65	0.40	"	1.06
131	2.4	"	2.5	128	0.79	"	1.07
....	....	......	....	193	1.22	"	1.09
195	3.2	"	2.84	255	1.70	"	1.15
131	2.1	"	2.78				
33	0.48	0.0331	2.53	381	−14.2	Charged 1 min. Discharged 15 sec. Then discharged through galvanometer	−6.47
66	0.90	"	2.38	440	−15.90		−6.27
129	1.88	"	2.53	315	−12.25		−6.75
194	2.80	"	2.50	250	−9.8		−6.80
259	3.80	"	2.53	190	−7.8		−7.11
324	4.76	"	2.55	128	−5.3		−7.17
388	5.78	"	2.58	64	−3.05		−8.25
452	6.70	"	2.57	32	−1.60		−8.66

This tests the principle of superposition by the constancy of the percentage of residual for a given charging interval. The air condenser gave at first a ballistic throw of 0.732 cms. per volt; after the line of dots an accident changed this to 0.580 cms. per volt; this sensitiveness was kept nearly constant thereafter. The air condenser has a larger capacity than the paraffin condenser. This explains the change of sign, with increasing time of charging in the ballistic throws. To get true percentages of residual formed in any interval we may, in this case, subtract the percentage values for the longer time from those of the shorter.

The principle of superposition may be here tested again, if we see whether the percentage values of residual throw are constant for every different charging interval. This condition is seen to be fairly well satisfied, perhaps as well as experimental errors allow, though, in the last block of observations there is a continual numerical decrease in the numbers as we go from lower to higher voltages. The conditions here were, however, somewhat different from those in the other cases. The condensers were charged for a minute, then discharged against each other and left in that connection 15 seconds, then discharged through the galvanometer.

Experiments with the Falling Weight Machine on the Residual Charges after Short-Circuiting.

As we see from the results obtained for residual charges formed in different charging intervals, as exhibited in the broken curves of Figure 2 which indicate the mean relative values of the residual-forming current during various increments of the charging time, this current is very much greater during the earlier than during the later stages of the charging. To investigate this matter for much shorter charging times the sliding weight armed with the six knife points in the manner described above was used. The first experiments were made after the manner shown in Figure 3, but without the use of the air condenser. The lead strips are shown below the diagram at **k** in the relative positions as seen by an observer in front of the machine, it being here assumed that the knife edges are all on the same horizontal level. It will be seen that the charging takes place through one of the right-hand or north knives, and through one of the east knives during the time necessary for the latter to plough across the surface of its lead strip.

The residual-forming current flows into the dielectric not only for this length of time, but also for the time necessary for the south knife

to reach the edge of its lead strip. While it cuts through this, the north knife still ploughing across its surface of lead, the potential difference of the test condenser is made zero. This short-circuiting lasts for, perhaps, 0.001 of a second or more, if a knife edge notches the whole edge of a lead strip, but may be as short as 0.00007 of a second, when a knife point barely notches the sharp edge of a lead strip which has been filed down to a narrow V-point. After the iron weight has been dropped from its trigger device and has thus charged and short-circuited the test condenser momentarily, a brief time is allowed the condenser for the residual charge to become "free," and then it is discharged through the d'Arsonval galvanometer.

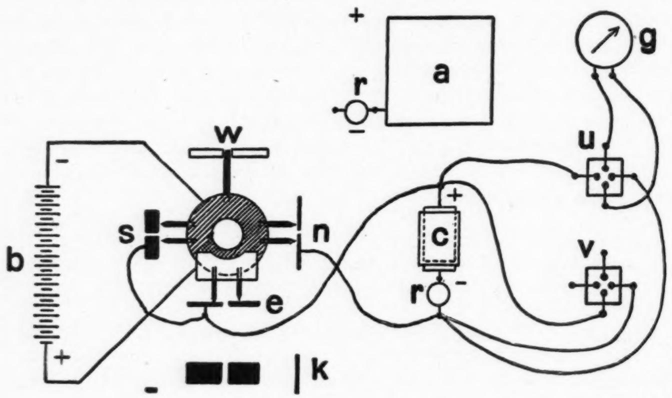

FIGURE 3.

The results obtained by these experiments are not of much quantitative value; for there is no way of knowing how much of the residual charge discharges during the short circuit along with the "free charge." What residual charge can form in 0.0032 of a second, which is the usual charging time in these experiments, is necessarily of a very mobile character, and perhaps a large part of it discharges in a short circuit even as brief as 0.00007 of a second. There is thus no reason to expect a number of measurements, taken under apparently the same conditions, to agree very closely; for a very slight difference in the time of short-circuiting may, perhaps, cause a large difference in the residual charge remaining behind.

As remarked above, the usual charging time in these experiments, or, more accurately, the time in which the test condenser is under the

TABLE V.

"Par. A."

	Volts.	Throw.	Charging Time.	Throw / Volts.
Jan. 31. Knife Edge Short Circuit.	128	0.42	0.0032	0.0033
	"	0.55	"	0.0043
	"	0.42	"	0.0033
	"	0.42	"	0.0033
	124	0.40	0.0016	0.0032
	"	0.28	"	0.0023 *
	"	0.37	"	0.0030
	"	0.33	"	0.0027
Feb. 6. Knife Edge Short Circuit.	122	1.76	0.57	0.0144
	"	1.90	"	0.0156
	"	1.28	0.111	0.0103
	"	1.92	0.57	0.0158
	"	1.98	"	0.0162
Feb. 7. Knife Point Short Circuit.	63	0.40	0.0032	0.0062
	123	0.88	"	0.0071
	"	0.78	"	0.0063
	"	0.69	0.0060	0.0056
	"	1.63	0.111	0.0133
	122	0.72	0.0032	0.0059
	"	0.73	0.0060	0.0060
	"	0.78	0.0032	0.0064
	121	0.57	"	0.0047 *
	"	0.78	"	0.0064
	"	0.91	veloc.	0.0075
	"	0.42	0.0032	0.0035 **

charging voltage, is 0.0032 of a second. But, by using a narrower strip of lead for the north knife to plough over, this time can be shortened. Again, two extra pairs of the lead strip holders were mounted

TABLE VI.

"MICA B_0".

	Volts.	Throw.	Charging Time.	Throw/Volts.
Feb. 7. Knife Point Short Circuit.	120	0.62	0.0032	0.0052
	"	2.22	0.1110	0.0185
	"	3.77	0.5700	0.0314
	"	0.62	0.0032	0.0052
	"	2.22	0.1110	0.0185
	"	3.67	0.5700	0.0306
	"	3.60	"	0.0300
	"	0.50	veloc.	0.0042

higher up on the north rod, so that the charging voltage could be applied for longer times. This accounts for the residual-forming intervals of 0.111 second and 0.57 second. For convenience in compar-

TABLE VII.

"PAR. B."

	Volts.	Throw.	Charging Time.	Throw/ Volts.
Feb. 8. Knife Point Short Circuit.	46	12.72	0.111	0.280
	28	6.80	"	0.240
	90	5.04	0.0032	0.056

ing results, values of the ballistic throws divided by the voltage are given so as to show the residual charge left in the condenser after short circuit, expressed in centimeters of throw per charging volt. The ballistic sensitiveness of the d'Arsonval galvanometer was such as

TABLE VIII.

"PAR. C."

	Volts.	Ballistic Throw.	Charging Time.	Throw/Volts.
Feb. 8. Knife Point Short Circuit.	94	7.32 + 0.65 + 0.18 = 8.15	0.0032	0.087
	"	6.10 + 0.60 + 0.32 = 7.02	"	0.075
	"	6.30 + 0.53 + 0.20 = 7.03	"	0.075
	93	6.00 + 0.50 + 0.12 = 6.62	"	0.071
	"	6.20 + 0.59 + 0.09 = 6.88	"	0.074
	180	10.40 + 1.10 + 0.11 = 11.61	"	0.065
	"	10.90 + 0.88 + 0.12 = 11.90	"	0.066
	264	14.90 + 1.30 + 0.12 = 16.32	"	0.062
	"	14.10 + 1.55 + 0.20 = 15.85	"	0.060
	420	23.20 + 2.07 + 0.30 = 25.57	"	0.061
	46	14.50 + 1.30 + 0.12 = 15.92	0.111	0.346
	28	14.80 + 1.47 + 0.40 = 16.67	0.570	0.559

TABLE IX.

"PAR. A."

	Volts.	Throw.	Charging Time.	Throw/Volts.
Feb. 12. Knife Point Short Circuit.	27.5	0.20	0.0032	0.0073
	113	0.78	"	0.0069
	220	1.34	"	0.0061
	"	3.14	0.111	0.0143
	"	5.75	0.570	0.0261
	"	5.58	"	0.0254
	"	3.40	0.111	0.0154
	"	1.38	0.0032	0.0063

to give a throw of 13.7 cms. per micro-coulomb of charge. The "free charge" capacities of the condensers are approximately as follows :

Air	0.0428 mf.
"Par. A"	0.041 "
"Par. B"	0.040 "
"Par. C"	0.047 "
"Mica B_0"	0.043 "

TABLE X.

"Par. A."		"Par. A."		"Mica B_0."	
Knife Edge. Volts : 122–128.		Knife Point. Volts : 65–123.		Knife Point. Volts : 120.	
Charging Time.	Throw /Volts.	Charging Time.	Throw /Volts.	Charging Time.	Throw/ Volts.
0.0016	0.0028	0.0032	0.0064	0.0032	0.0052
0.0032	0.0034	0.111	0.0133	0.111	0.0185
0.111	0.0105			0.57	0.0307
0.57	0.0155				

"Par. A."		"Par. B."		"Par. C."		
Knife Point. Volts : 113–220.		Knife Point. Volts : 28–90.		Knife Point. Volts : 28–420.		
Charging Time.	Throw /Volts.	Charging Time.	Throw /Volts.	Volts.	Charging Time.	$\frac{\text{Thr.}}{\text{Volts.}}$
0.0032	0.0065	0.0032	0.056	94	0.0032	0.076
0.111	0.0149	0.111	0.260	180	"	0.065
0.57	0.0258			264	"	0.061
				420	"	0.061
				46	0.111	0.35
				28	0.57	0.56

Table V gives the detail of the observations taken under these conditions.

The next to the last observation of Table V was taken under the same conditions as for a time of 0.0032 seconds, save that the weight was given an acceleration by hand. This shortened both the times of charging voltage and short circuit in much the same proportion, but the larger throw indicates that the change of time of short circuit was of greater influence. For the starred observations, the short circuits were longer than for the others.

The residual charges in "Par. B" and "Par. C" of Tables VII and VIII had to be short-circuited several times through the galvanometer, since the first discharge did not take away all of the residual formed.

Table X contains a summary of mean results.

Experiments with the Falling Weight Machine, using the "Test Condenser versus Air Condenser" Method.

I now decided to make observations on the actual quantities of residual charge formed in various short charging intervals by using the air condenser to neutralize approximately the whole of the "free charge" of the test condenser, and then measuring the remainder ballistically. The method used from now on till the end of the work was quite similar to the former one in which the knife switches were used and the relay lever changed circuits so that the charge of the air condenser neutralized nearly all the charge of the test condenser. But the relay was now discarded, since its use made the time of charging impossible to control when very short, and it was found best to let the falling weight machine do the charging merely, while the neutralization of the charges was effected by lowering a commutating key by hand immediately after. Then after a short pause, which varied according to the quickness with which the residual charge reappeared, the remaining charge was sent through the galvanometer by lowering another commutating key.

The arrangement of the apparatus and connections is shown in the accompanying diagram (Figure 4). One of the north knives is no longer necessary. The chief points of difference from the short-circuiting method of experimenting are: (*a*) the addition of the air condenser **a**, and (*b*) the slight raising of the block on which the south lead strip holders **s** are mounted as indicated in the relative positions at **k**. The new arrangement changes the former short-circuiting action over into a charging action. The air condenser was as a rule uniformly charged by means of a knife edge cutting the edge of a lead strip clamped

horizontally by one of the south holders (**s**, upper one), while at the same time one of the high voltage east knives ploughed over the surface of its lead strips, shown at **e**. The test condenser **c** could be charged either by means of the north knife, which gives from one to two centimeters of ploughing contact, or by means of lead strips placed in the other south lead clamp. The time of charging could here be varied by letting a knife point notch the edge of one, two, or three thicknesses of lead strips (**s**, lower strip), placed together with their edges all even, or by letting the sharp knife point barely dent the sharpened edge of a single lead strip, as in the short-circuiting experiments. By

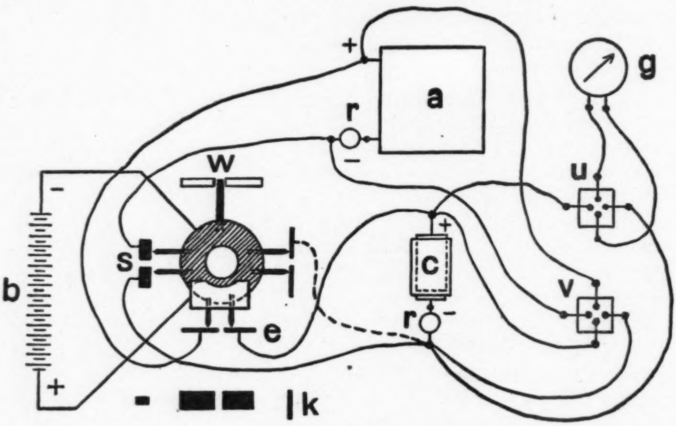

FIGURE 4.

the use of very fine knife points and very sharp edges of the lead strip it was estimated that charging times as short as 0.00005 of a second could be obtained, if the lead strip was carefully adjusted so that the knife point would just slightly notch the sharpened edge. More often the time would be about 0.00007 of a second, and this number is usually taken in reducing the observations. Each thickness of lead strip adds 0.00012 second to the charging time, but the number 0.00020 has been adopted as the charging interval when the knife point notches the whole edge (0.7 mm.) of a single lead strip, because in this case the strip was not adjusted to be notched on quite so narrow a margin. The height above these lead strips, from which the iron weight with the knives was usually dropped and for which the

figures have been given, is about 185 cms.; this was the highest drop obtainable on the machine.

The method of procedure was as follows: after a test condenser of capacity very nearly equal to that of the air condenser had been connected up as shown in the diagram, while the battery circuit was still open, the iron weight was raised a little above the lead strips, and these were clamped after having been properly adjusted, so that the knife edges should plough furrows of moderate depth on the surfaces of the lead. Then the iron weight was pushed up into its trap (**k**, Figure 1), and the commutating key **v** of the condensers, which had thus far kept both condensers short-circuited, was lifted from the mercury wells. The battery circuit was now closed, thus keeping the brass plate of the east knives at high potential, and the iron weight with the north and south knives at low potential. The observer now brought the coil of the d'Arsonval galvanometer **g** to rest, pulled with the right hand the string which released the iron weight, and at the moment when the iron weight was heard to strike into the dash pot he dropped the commutator key **v** into its mercury wells in the neutralizing position, connecting the positive terminal of each condenser with the negative plate of the other. The condensers destroyed each others' charges approximately, leaving a remainder which was then sent through the galvanometer by dropping the galvanometer key **u** into its mercury wells. The ballistic throw was read and recorded, together with the voltage of the battery and the conditions controlling the charging interval. Then, if there were no secondary residual charges, the condensers were short-circuited by their commutating key, the galvanometer coil was brought to rest by short-circuiting its terminals, the key of the storage battery was opened so as to protect the battery from a possible short circuit while the lead strips were loosened and drawn aside, and the iron disk in the dash pot was pulled up to its normal position. Then operations were repeated.

The experiments just described were begun on February 10, and carried on until March 27, 1908. The earlier results were not of the high accuracy which characterizes nearly all the observations taken on and after March 10. It was at one time suspected that the storage battery could not respond fully to demands in the very short charging intervals. But the real cause of occasional disagreements in the ballistic throws obtained was later found to lie in imperfect contacts of the storage battery leads on the switch-board. I shall merely summarize below the results obtained in the earlier part of the work on various test condensers, by giving mean values of several observations, and their reduction to the final values of residual charge expressed in per-

centage of total "free charge," without giving all the individual observations. The meaning of the positive and negative ballistic throws and the method of making the reductions is fully described on page 500, in connection with the results of March 10 and 11.

It should be noted here that various resistance coils, from 5 to 85 ohms and higher, were used in the condenser circuits, connected directly to one of their terminals as indicated by small circles (rr) in the diagram. Usually, however, the air condenser had a 10 ohm coil, and the test condenser a 5 ohm coil, connected to it. The exact value of the resistance is not important; the object of the resistance is merely to prevent too great an initial rush of charge.

All the pieces of apparatus, the storage battery, the falling weight machine, the condensers, the commutating keys, and the galvanometer, were carefully insulated by means of large porcelain knobs or blocks of paraffin. These were often cleaned and scraped and, so far as could be ascertained, none of the troubles experienced were due to leakage of any kind. It will be noticed later that the air condenser and most of the test condensers have a small internal conductivity, but as the operation of neutralizing the charges takes place immediately after the charging, this conductivity could not result in a measurable loss of charge from either condenser.

On February 26 a condenser made up of 12 separate commercial paraffined paper condensers, giving a total capacity of about 50 microfarads, was connected across the terminals of the storage battery. This was done to avoid a possible source of trouble in that the battery might not be able to furnish complete charges for the test condenser in the very short charging intervals. It was found to be useful, but the

TABLE XI. (Figure 7.)

"Par. A" *vs.* Air. February 11.

No. Obs.	Volts.	Throw.	Charging Time.	Throw/Volts.	Residual Throw.	Percentage Residual.
3	124	4.17	0.00010	0.0336	(0)	(0)
6	124	3.84	0.00015	0.0310	+0.0026	0.47
5	124	3.70	0.00020	0.0299	+0.0037	0.67
1	124.5	3.56	0.00032	0.0286	+0.0050	0.90
2	124.5	3.45	0.00044	0.0277	+0.0059	1.07

TABLE XII. (Figure 8.)

"Par. B" *vs.* Air. February 11.

No. Obs.	Volts.	Throw.	Charging Time.	Throw/Volts.	Residual Throw.	Percentage Residual.
2	126	5.16	0.00010	0.0410	(0)	(0)
2	125.5	3.85	0.00020	0.0302	+0.0108	2.00
2	125	2.95	0.00032	0.0236	+0.0174	3.21
2	125	2.62	0.00044	0.0210	+0.0200	3.50

TABLE XIII.

"Shellac-Mica" *vs.* Air. February 20.

No. Obs.	Volts.	Throw.	Charging Time.	Throw/Volts.	Residual Throw.	Percentage Residual.
2	240	1.14	0.00007	0.0048	(0)	(0)
1	58	0.17	"	0.0030		
1	124	−1.94	60 secs.	−0.0156	+0.0215	2.7
1	122.5	−2.76	3 min.	−0.0225	+0.0274	4.7

TABLE XIV. (Figure 5.)

"Mica B" *vs.* Air. February 21.

No. Obs.	Volts.	Throw.	Charging Time.	Throw/Volts.	Residual Throw.	Percentage Residual.
2	129	− 1.51	0.00007	0.0117	(0)	(0)
2	130	− 1.99	0.00020	0.0153	+0.0036	0.6
2	115	− 2.33	0.0025	0.0202	+0.0085	1.4
2	115	− 3.73	0.111	0.0325	+0.0208	3.4
1	117	− 5.20	0.57	0.0445	+0.0328	5.4
1	115	− 9.0	20 secs.	0.0781	+0.0664	10.8
1	115	−15.9	2 min.	0.138	+0.1260	20.6

TABLE XV. (Figure 5.)

"MICA A" *vs.* AIR. FEBRUARY 21.

No. Obs.	Volts.	Throw.	Charging Time.	Throw/Volts.	Residual Throw.	Percentage Residual.
2	130	−0.40	0.00020	0.0031	(0)	(0)
2	130	−0.66	0.0025	0.0051	+0.0020	0.34
2	130	−1.70	0.111	0.0131	+0.0100	1.7
1	129	−2.50	0.57	0.0194	+0.0163	2.7
1	123	−4.59	5 secs.	0.0373	+0.0342	5.7
1	123	−7.26	40 secs.	0.0590	+0.0560	9.4
1	114	−8.39	2 min.	0.0735	+0.0700	11.7

TABLE XVI. (Figure 5.)

"MICA B" *vs.* AIR. FEBRUARY 22.

No. Obs.	Volts.	Throw.	Charging Time.	Throw/Volts.	Residual Throw.	Percentage Residual.
3	122	−1.61	0.00007	0.0132	(0)	(0)
2	119	−1.73	0.00020	0.0145	+0.0013	0.21
1	122	−2.50	0.0025	0.0205	+0.0073	1.2
1	122	−3.66	0.111	0.0300	+0.0168	2.8
2	112	−1.61	0.00007	0.0143	(0)	(0)
1	112	−1.81	0.00020	0.0162	+0.0019	0.31

TABLE XVII. (Figure 5.)

"MICA A" *vs.* AIR. FEBRUARY 22.

No. Obs.	Volts.	Throw.	Charging Time.	Throw/Volts.	Residual Throw.	Percentage Residual.
2	119	−0.35	0.00020	0.0029	(0)	(0)
3	118	−0.50	0.0032	0.0042	+0.0013	0.22
3	116	−1.64	0.111	0.0141	−0.0112	1.9

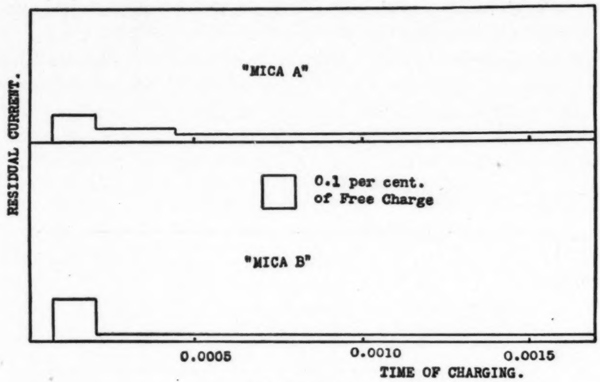

FIGURE 5.

(Tables XXVII, XXIX, XXXII, XXXIII, XXXVII, XXXVIII.)

TABLE XVIII. (Figure 6.)

"PAR. BB" *vs.* AIR. FEBRUARY 29.

No. Obs.	Volts.	Throw.	Charging Time.	Throw/Volts.	Residual Throw.	Percentage Residual.
2	133.5	−3.71	0.0025	0.0277	(0)	(0)
3	132	−4.80	0.111	0.0363	+0.0086	1.5
2	132	−5.22	0.57	0.0394	+0.0117	2.04

TABLE XIX. (Figure 5.)

"MICA B" *vs.* AIR. FEBRUARY 29.

No. Obs.	Volts.	Throw.	Charging Time.	Throw/Volts.	Residual Throw.	Percentage Residual.
4	125	−2.88	0.00007	0.0230	(0)	(0)
2	128	−3.03	0.00007	0.0237		
3	128	−3.36	0.0025	0.0262	+0.0032	0.52

50 microfarad condenser should not have much internal leakage, as this would run down the voltage of the storage battery too fast. The test-tube cells of the battery naturally have not a large current capacity, but they are excellent for giving a steady difference of potential and small charges such as are required for these experiments. In the case of each condenser the first residual throw is assumed to be zero.

The mean results reduced for the experiments up to March 10 are shown in the preceding nine tables.

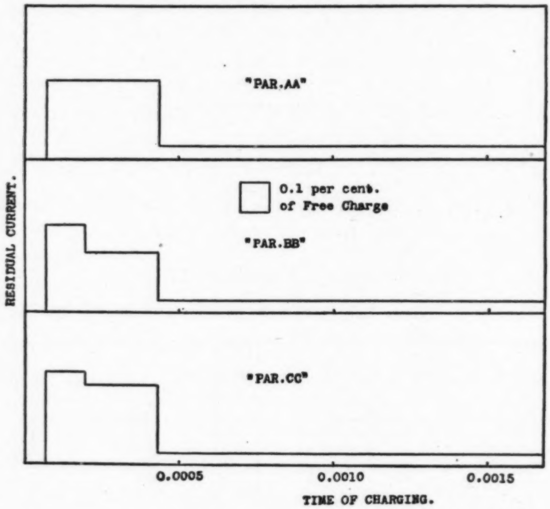

FIGURE 6. (Tables XXVIII, XXX, XXXI, XXXIII.)

By comparing these summarized results of Tables XI–XIX with those which are to follow, we see that they do not all agree very well. But there is a substantial similarity in the behavior of the various condensers, and some condensers, as "Par. A," "Par. B," "Par. AA," and "Par. BB," show very close agreement with results as determined more accurately later. The results from the mica condensers are not so good.

It will be seen that the condensers of plain mica sheets show a very much greater residual capacity for long charges than the condenser made of shellacked mica sheets. This is hardly what we should have expected, according to Maxwell's heterogeneity theory.

After the preliminary experiments had been made the whole network of conductors was overhauled, and many of the joints were soldered with the help of white pitch as a flux. Sometimes in the later work the 50 microfarad condenser was connected across the poles of the charging battery but seemed not to be necessary. Local conditions made it difficult to bring the coil of the d'Arsonval galvanometer quite to rest and some of the throws had to be made when the coil was swinging over a double amplitude of half a millimeter.

In the tables given below the charging intervals are expressed in terms of the amount of the lead cut through by the knife point. It was calculated that

1 centimeter	means	0.0017	seconds	of	charge
3 lead widths	"	0.00044	"	"	"
2 lead widths	"	0.00032	"	"	"
1 lead width	"	0.00020	"	"	"
very short	"	0.00007	"	"	"
extra short	"	0.00005	"	"	"

Observations, March 10.

TABLE XX. (Figure 7.)

"PAR. A" *vs.* AIR.

Volts.	Throw.	Charging Time.
132	4	very short
"	3.98	" "
"	3.80	1 width
128	3.8	"
"	3.78	"
"	4.3	very short
"	4.32	extr. short
"	4.30	" "

TABLE XXI. (Figure 6.)

"PAR. BB" *vs.* AIR.

Volts.	Throw.	Charging Time.
128	2.29	extr. short
"	2.20	" "
"	2.29	" "
"	2.02	1 width
128	2.01	"
124	1.96	"

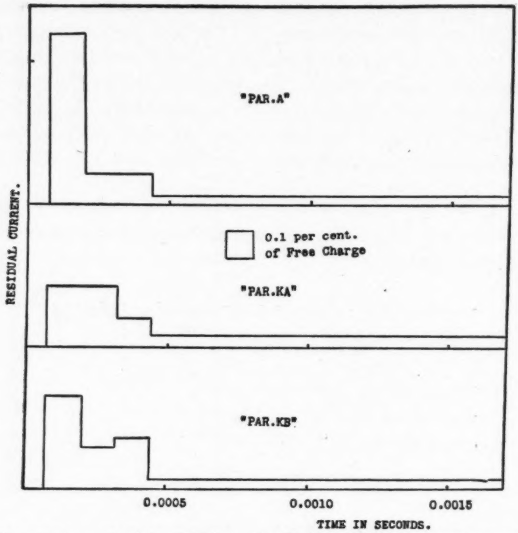

FIGURE 7. (Tables XXVI, XXXIV–XXXVI, XXXVIII.)

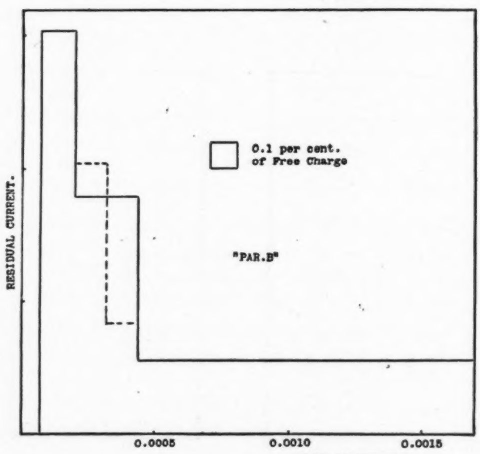

FIGURE 8. (Tables XLII and XLIII.)

TABLE XXII. (Figure 5.)

"MICA B" *vs.* AIR.

Volts.	Throw.	Charging Time.
124	−3.19	2 widths
"	−3.15	"
"	−3.13	"
"	−3.05	very short
123.5	−3.02	" "
123	−3.07	short
"	−3.13	1 width
122.5	"	"
120	−3.09	2 widths
"	−3.10	"

TABLE XXIII. (Figure 5.)

"MICA A" *vs.* AIR.

Volts.	Throw.	Charging Time.
132	−1.51	very short
133	−1.53	" "
"	−1.61	1 width
132	−1.57	2 widths
"	−1.63	"
"	−1.58	"
"	−1.50	very short
131.5	−1.52	" "
"	−1.53	" "

TABLE XXIV. (Figure 6.)

"PAR. AA" *vs.* AIR.

Volts.	Throw.	Charging Time.
131.5	1.39	very short
"	1.30	" "
"	1.35	" "
"	1.42	" "
131	0.99	2 widths
"	0.98	"
"	1.19	1 width
131−	1.21	"
130.5	1.30	"
127	1.26	"

TABLE XXV. (Figure 6.)

"PAR. CC" *vs.* AIR.

Volts.	Throw.	Charging Time.
127	1.88	1 width
"	2.10	very short
125	2.13	extr. short
"	1.64	2 widths
"	1.81	"
"	1.73	"
"	1.79	"

Observations, March 11.

TABLE XXVI. (Figure 7.)

" PAR. A " *vs.* AIR.

	Volts.	Throw.	Charging Time.	Temp.
A. M.	130	3.50	2 widths	
	"	3.49	"	
	"	"	"	
	"	4.30	extr. short	
	"	4.01	very short	
	"	4.21	" "	
	"	4.13	" "	
	"	3.72	1 width	
	"	3.74	"	
	129.5	3.63	"	
	"	3.67	"	
	125	3.57	3 widths	
	124	3.54	"	
	123	3.50	"	
	"	3.52	"	22°.0
	"	3.31	1 cm.	
	121	3.28	"	
	120	3.22	"	
	119	3.17	"	
	128	3.18	"	
	"	"	"	
	"	3.40	"	
	"	3.21	"	
P. M.	132	2.90	1 cm.	
	"	2.92	"	
	"	3.23	3 widths	
	"	3.14	"	
	"	3.31	"	
	"	3.20	"	

TABLE XXVII. (Figure 5.)

"MICA B" *vs.* AIR.

Volts.	Throw.	Charging Time.	Temp.
132	−3.32	3 widths	
"	−3.28	"	
"	−3.32	"	21°.8
"	−3.61	1 cm.	
"	−3.63	"	

TABLE XXVIII. (Figure 6.)

"PAR. BB" *vs.* AIR.

Volts.	Throw.	Charging Time.	Temp.
132	1.39	1 cm.	
"	"	"	
"	1.64	3 widths	21°.8
"	1.84	"	
"	1.70	"	

TABLE XXIX. (Figure 5.)

"MICA A" *vs.* AIR.

Volts.	Throw.	Charging Time.
132	−1.67	3 widths
"	−1.68	"
"	−1.89	1 cm.
"	−1.88	"

TABLE XXX. (Figure 6.)

"PAR. CC" *vs.* AIR.

Volts.	Throw.	Charging Time.
131+	1.11	1 cm.
132	1.13	"
"	1.48	3 widths
"	"	"

TABLE XXXI. (Figure 6.)

"PAR. AA" *vs.* AIR.

Volts.	Throw.	Charging Time.	Temp.
132 –	0.62	3 widths	
131	0.58	"	
131 +	0.59	"	
"	0.20	1 cm.	22°.7
131	0.21	"	
"	1.30	extr. short	
131 –	1.08	very short	
"	1.33	extr. short	

TABLE XXXII. (Figure 5.)

"MICA B" *vs.* AIR.

Volts.	Throw.	Charging Time.	Temp.
131	–3.22	very short	
"	–3.32	" "	23°.0
"	–3.23	" "	
"	–3.28	" "	

In working up the data here printed to derive the results shown in Table XXXIII, below, the following method was used:

I first determined from the observations the ratios (R) of the throw obtained to the charging voltage and set the R's opposite the corresponding charging intervals. Then I found mean values of the R's for the various charging intervals. Then that R which I believed to correspond to the shortest charging interval secured was taken as a standard of comparison and the unknown residual charge in centimeters of throw per volt which had already been formed in the condenser in this shortest obtainable charging interval was called x. By taking

the difference between this standard R and the R corresponding to any other charging interval and calling this difference d, I got $(x+d)$ for the residual charge which formed in the other interval. I then divided all the numbers $(x+d)$ by the total charge per volt which went into the test condenser in the shortest charging time. This gave numbers which are independent of the apparent capacity of the test condenser used. When multiplied by 100, these give the residual charges formed in the given charging times, expressed in percentage of the total charge formed in the shortest time.

Thus in Table XXVI we have for the condenser "Par. A" a capacity of 0.0404 mf., or 0.554 cm. when expressed in ballistic throw per volt. Then for "Par. A," let $x(100)/0.554 = y$. Then for "1 width" of charge $(x + 0.0044)(100)/0.554 = y + 0.80$; and the number $(y + 0.80)$ will be the residual charge which forms in the charging time of 0.00020 second, expressed in percentage of the total charge formed in the condenser "Par. A" in the charging time 0.00005 second. We shall express the results obtained in the $(y+d)$ form for all the test condensers, but must remember that the y is in general widely different for the different condensers. We thus obtain the following table:

TABLE XXXIII. (Figures 5, 6, and 7.)

Residual Charge in Percentage of Total Charge.

March 10, 11, 1908. Temp. = 22°–23°.

Condenser.	Time of Charge in Seconds.				
	0.00005	0.00020	0.00032	0.00044	0.00170
"Par. A"	y	$y + 0.80$	$(y + 1.14)$?	$y + 1.06$	$y + 1.48$
"Par. AA"	y	$y + 0.22$	$y + 0.51$	$y + 0.95$	$y + 1.47$
"Par. BB"	y	$y + 0.37$	....	$y + 0.83$	$y + 1.30$
"Par. CC"	y	$y + 0.39$	$y + 0.56$	$y + 1.02$	$y + 1.49$
"Mica A"	y	$y + 0.105$	$y + 0.102$	$y + 0.20$	$y + 0.48$
"Mica B"	y	$y + 0.17$	$y + 0.20$	$(y + 0.11)$?	$y + 0.48$

A great difference will be immediately observed between the paraffin condensers and the mica condensers. The variation is large in the

paraffin, while in mica there is almost no variation in the region of charging intervals considered. And if we examine the original throws observed, we find that for the very short charging times the throws vary greatly in case of paraffin, while for the mica they are practically constant. All the paraffin condensers show close agreement in their behavior, and so do the two mica condensers. (See figures 5, 6, and 7.)

Observations of March 12 *and* 13.

The following tables (XXXIV–XXXVIII) give mean values of ballistic throws observed and reductions. The condensers "Par. KA" and "Par. KB" are built of the same paraffined paper as the others, but the sheets were merely piled together without the use of the hot flat-iron. Thus we have layers of air as well as the paper sheets as the dielectrics.

TABLE XXXIV. (Figure 7.)

"Par. KA" *vs.* Air.

No. Obs.	Volts.	Ballistic Throw.	Charging Time.	$\frac{\text{Throw}}{\text{Volts.}}$	Residual Charge in cms. /Volts.	Temp.
1	133	−0.91	0.00007	0.0068	x	
1	"	−1.86	0.0017	0.0140	$x + 0.0072$	
1	132	−1.50	0.00005	0.0114	x	
1	133	−1.78	0.00007	0.0134	....	
6	"	−2.36	0.0017	0.0177	$x + 0.0063$	
1	"	−1.60	0.00007	0.0120	....	
2	132	−2.55	0.0017	0.0193	$x + 0.0073$	
2	131.5	−2.505	0.00044	0.0190	$x + 0.0039$	
2	"	−2.95	0.0017	0.0224	$x + 0.0073$	21°.2
2	"	−2.41	0.00032	0.0183	$x + 0.0032$	

TABLE XXXV. (Figure 7.)

" PAR. KB " *vs.* AIR.

No. Obs.	Volts.	Ballistic Throw.	Charging Time.	$\frac{\text{Throw}}{\text{Volts}}$.	Residual Charge in cms./Volts.	Temp.
4	132	−3.40	0.00020	0.0258	$x + 0.0026$	
2	"	−3.55	0.00032	0.0269	$x + 0.0037$	
2	"	−3.73	0.00044	0.02825	$x + 0.00505$	20°.6
2	"	−4.12	0.0017	0.0312	$x + 0.0080$	
2	"	−3.06	0.00007	0.0232	x	
1	123	−1.61	0.0017	0.0131	$x + 0.0080$	
1	"	−0.63	0.00007	0.0051	x	

TABLE XXXVI. (Figure 7.)

"PAR. A " *vs.* AIR.

No. Obs.	Volts.	Ballistic Throw.	Charging Time.	Throw/Volts.	Residual Ch. in cms./Volts.	Temp.
3	132	3.11	0.0017	0.0236	$x + 0.0053$	
1	"	3.81	0.00007	0.0289	x	20°.6
1	"	3.46	0.00020	0.0262	$x + 0.0027$	

TABLE XXXVII. (Figure 5.)

" MICA A " *vs.* AIR.

No. Obs.	Volts.	Ballistic Throw.	Charging Time.	Throw/Volts.	Residual Ch. in cms./Volts.	Temp.
2	132	−1.41	0.0017	0.0107	$x + 0.0006$	20°.6
1	"	−1.33	0.00007	0.0101	x	

From these we get

TABLE XXXVIII. (Figures 5 and 7.)

RESIDUAL CHARGE IN PERCENTAGE OF TOTAL CHARGE.

March 12, 13, 1908. Temp. = 20°–22°.

Condenser.	Time of Charge in Seconds.				
	0.00007	0.00020	0.00032	0.00044	0.00170
" Par. KA "	y	...	$y + 0.53$	$y + 0.65$	$y + 1.22$
" Par. KB "	y	$y + 0.43$	$y + 0.61$	$y + 0.83$	$y + 1.31$
" Par. A "	y	$y + 0.48$	...	...	$y + 0.95$
" Mica A "	y	...	...	...	$y + 0.10$

We see from these results that the layers of air in the condensers "Par. KA" and "Par. KB" apparently make little, if any, difference in the amount of residual charge.

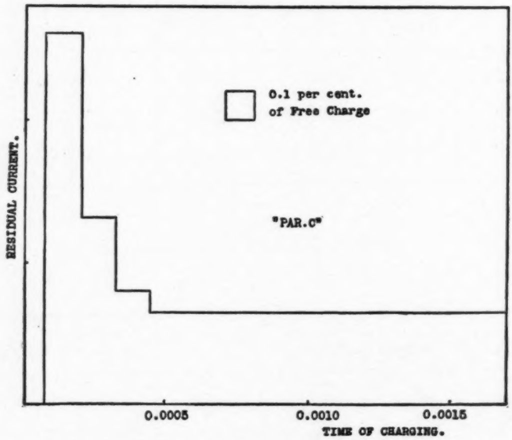

FIGURE 9. (Tables XLI and XLIII.)

Observations of March 17, 1908.

TABLE XXXIX. (Figure 11.)

GLASS CONDENSER *vs.* AIR.

Volts.	Throw.	Charging Time.	Throw / Volts.	Residual Charge in cms. per Volt.	Temp.
104	0.68	0.0017	0.00654	$x + 0.0087$	
103	0.58	"	0.00563	$x + 0.0096$	
"	0.52	"	0.00505	$x + 0.0101$	
102	1.48	0.00007	0.0145	...	
100	1.51	"	0.0151	...	21°.1
"	1.52	"	0.0152	x	
98	1.15	0.00020	0.01175	$x + 0.0036$	
97	1.11	"	0.01145	...	
132.5	1.39	0.00020	0.01010	$x + 0.0044$	
133	1.44	"	0.01075	$x + 0.0038$	
"	0.77	0.0017	0.00579	$x + 0.0088$	
"	0.68	"	0.00507	$x + 0.0095$	15°.0
"	1.67	"	...	...	
"	1.53	0.00020	0.0116	$x + 0.0030$	
"	1.55	"	...	...	
132.5	1.37	0.00032	0.0104	$x + 0.00415$	
"	1.39	"	...	...	
"	1.41	0.00044	...	...	
"	1.33	"	0.0102	$x + 0.00435$	
132	1.31	"	...	...	
"	0.85	0.0017	...	...	
"	0.84	"	0.00647	$x + 0.0081$	15°.5
"	0.87	"	...	...	
"	1.37	0.00044	0.01022	$x + 0.00433$	
"	1.33	"	...	...	
"	1.69	0.00007	0.0128	...	
"	1.92	"	0.01455	x	

To equal approximately the capacity of the glass condenser, only the six uppermost air layers were used; the capacity of this new air condenser was 0.0207 mf., and that of the glass condenser for very short charges about 0.0196 mf. We get —

TABLE XL. (Figure 11).

RESIDUAL CHARGE IN PERCENTAGE OF FREE CHARGE. GLASS.

Charging Time.	Residual.	Temp.	Charging Time.	Residual.	Temp.
0.00020	$y + 1.34$	21 C.	0.00020	$y + 1.30$	15° C.
0.00170	$y + 3.54$		0.00032	$y + 1.55$	
			0.00044	$y + 1.62$	
			0.00170	$y + 3.25$	

Observations of March 18, 1908.

TABLE XLI. (Figure 9).

" Par. C " *vs.* AIR.

Volts.	Throw.	Charging Time.	$\frac{\text{Throw}}{\text{Volts}}$.	Residual Charging.	Temp.
132	−12.00	0.0017	0.0910	...	
"	−12.53	"	0.0950	$x + 0.044$	
133	− 7.54	0.00007	0.0567	...	
132.5	− 6.53	"	0.0493	x	15°.0
"	− 6.83	"	0.0515	...	
"	−12.41	0.0017	0.0942	$x + 0.045$	
131.5	− 7.95	0.00020	0.0605	...	
131	− 7.80	"	0.0598	$x + 0.0108$	
117	− 8.55	0.00044	0.0731	...	
"	− 8.67	"	0.0741	$x + 0.0181$	
116	− 8.12	0.00032	0.0700	...	
114	− 8.00	"	0.0702	$x + 0.0151$	
113	−11.14	0.0017	0.0986	...	15°.3
"	−11.19	"	0.0992	$x + 0.044$	

TABLE XLII. (Figure 8.)

"Par. B" *vs.* Air.

Volts.	Throw.	Charging Time.	$\frac{\text{Throw}}{\text{Volts.}}$	Residual Charging.	Temp.
131	3.91	0.00020	0.0299	$x + 0.0115$	
"	4 12	"	0.0314	$x + 0.0100$	
130	5.38	0.00007	0.0414	x	
128	5.21	"	0.0407	...	
130	4.10	"	0.0316	...	15°.0
130+	4.35	"	0.0334	...	
130	4.54	"	0.0349	...	
"	+0.25	0.0017	0.0019	...	
128	(−0.42)	"	(−0.0033)	$(x + 0.042)$	
"	(0)	"	(0)	...	
120	2.93	0.00032	0.0244	$x + 0.0162$	
119	3.09	"	0.0260	...	
117	2.20	0.00044	0.0188	...	15°.3
"	2.29	"	0.0196	$x + 0.0224$	
"	2.18	"	0.0186	...	

These condensers, "Par. C" and "Par. C_1," are the ones which were made with paraffined paper soaked in wax only moderately warm, so that the air bubbles of the paper were not expelled. They show enormous residual capacity; in fact, to get the throws for "Par. C" four residual charges had to be read by the galvanometer, besides the first throw directly after neutralization of the charges of the air condenser and the test condenser.

The bracketed values in the last set of observations were obtained by reversing the terminals of the "Par. B" condenser. After these two readings the terminals were changed back again. The bracketed figures, when compared with those immediately preceding and following, show a curious "set" in the polarization. This point deserves further study, and it is hoped that it may sometime be taken up at length.

We derive the following values for the

TABLE XLIII. (Figures 8 and 9.)

RESIDUAL CHARGE IN PERCENTAGE OF TOTAL CHARGE.

Condenser.	Time of Charge in Seconds.				
	0.00007	0.00020	0.00032	0.00044	0.00170
" Par. C "	y	$y + 1.70$	$y + 2.37$	$y + 2.85$	$y + 6.92$
" Par. B "	y	$y + 1.97$	$y + 2.97$	$y + 4.12$	$y + 7.72$

It will readily be seen that these two condensers show very close family resemblance.

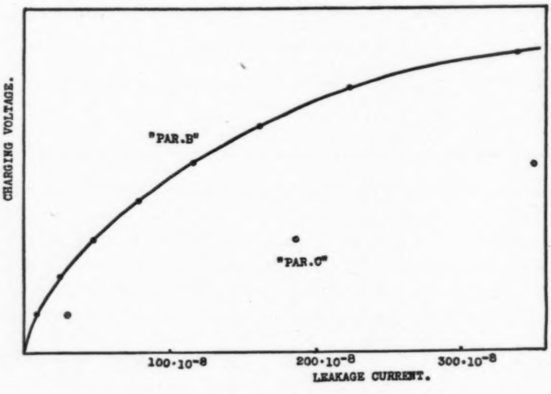

FIGURE 10. (Table XLIV.)

"Insulation Resistances" of the Condensers.

The following observations were taken on March 19 and March 27. The pure paraffin condensers and the air condenser were measured for leakage on the later date.

TABLE XLIV. (Figure 10.)

Condenser.	Volts.	Steady Deflections in cms.	Current in amp.
"Par. A"	325	0.13	1.43×10^{-8}
"Par. AA"	328	0.02	0.22 "
"Par. BB"	"	0.03	0.33 "
"Par. CC"	"	"	" "
"Par. KA"	"	0.09	0.99 "
"Par. KB"	"	0.10	1.10 "
"Mica A"	"	0.02	0.22 "
"Mica B"	"	0.04	0.44 "
"Par. C"	65	2.75	30.30 "
"	328	32.00	352.00 "
"	195	17.00	187.00 "
"Par. B"	66	0.86	9.46 "
"	131	2.33	25.60 "
"	195	4.40	48.40 "
"	262	7.17	78.90 "
"	328	10.57	116.30 "
"	390	14.72	161.90 "
"	457	20.40	224.40 "
"	517	11.00	341.00 "
"P"	518	0	0 "
"Q"	"	0.03	0.33 "
"R"	"	0.10	1.10 "
Air	510	0.13	1.43 "

The sensitiveness of the d'Arsonval galvanometer in measuring steady currents is 9.1×10^6 cms. per ampere of current.

The leakage currents given are, as a rule, near the maximum values, for most of the currents were slowly decreasing with the time when they were taken. But "Par. B" showed a marked *increase* of the current with the time.

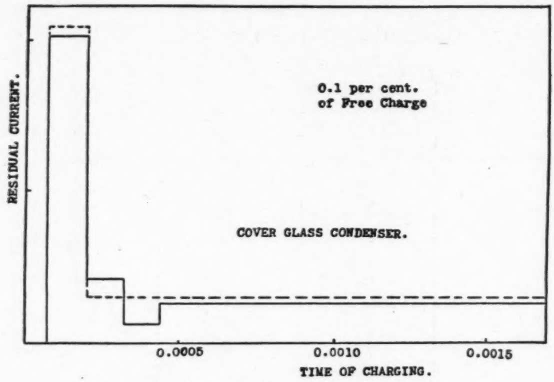

FIGURE 11. (Tables XXXIX and XL.)

The Condensers of Pure Paraffin Sheets.

The preparation of thin slabs of pure paraffin for use as the dielectric of a parallel plate condenser for experimental purposes has always been a difficult task. Boltzmann recommends that the melted paraffin be poured between two plates of plate glass whose inner surfaces have been coated over with a thin film of oil, in order that the slab may be readily separated from the plates after it has cooled and become hard. This leaves thin films of oil over both surfaces of the paraffin slab, and these should be scraped off before the slab can be used. The writer made some fairly thin slabs three years ago by pouring hot paraffin into a square frame of wood placed on a single plate of glass lying horizontally and having a film of oil to allow the later separation of the paraffin. But he has never yet seen any paraffin so formed which was free from air bubbles or small cavities. It is possible, and perhaps after all the easiest way, to saw off slabs of paraffin from a large block and then to plane down the surfaces, but this will not give very thin slabs.

It occurred to the writer that perhaps thin sheets of paraffin might be made by the same method which is used to obtain thin sheets of beeswax, such as are manufactured into "comb foundation" for use in modern apiaries. A trial experiment on a small scale proved completely successful. Smooth sheets of paraffin were obtained as thin as sheets of paper and apparently quite homogeneous. Then the necessary apparatus was secured to make the sheets of parraffin larger and

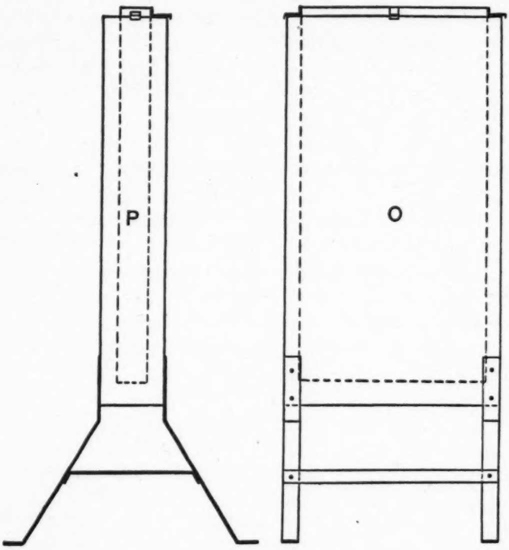

FIGURE 12.

Side Views of Dipping Tanks.

in great numbers. Two tanks were constructed (Figure 12) by a plumber, according to the following specifications: The material used was galvanized sheet iron (copper sheeting, however, would be more durable). One tank, which was to hold hot paraffin, was to hang inside the other one, in which water was to be kept heated to the proper temperature by means of Bunsen burners. The dimensions were: inner tank: height, 61 cms., base, 30.5 by 5.1 cms.; outer tank: height, 63.5 cms., base 35.6 cms. by 10.5 cms. The inner tank had three projecting strips of galvanized iron, bent down near their ends,

which just reached over the top rim of the outer tank, and held the inner one at such a height that its top was about 1.8 cms. higher than the top of the larger tank. This was done to keep the water from getting from the outer tank into the inner one.

Meanwhile two "dipping boards" were obtained. These were made of light pine (whitewood may be better) and are 61 cms. long, 25 cms. wide, and about 0.5 cms. thick. They are bevelled down to a narrow V-shape along both of the long edges and one end. Near the other end a hole is bored through, so that each board can be hung from a hook. These boards are carefully planed, and then sand-papered until they have a very smooth surface and are free from loose fibres of wood.

A day or two before the paraffin sheets are to be "dipped," the two dipping boards are wholly immersed in water and left there until needed. Before this immersion strips of wood should be tied across the boards so as to keep them from warping when they become thoroughly water-soaked. This must also be done after the work of making the paraffin sheets is finished, and the boards are to be allowed to dry; otherwise they will surely warp in drying. When the boards have become thoroughly water-soaked, the paraffin is melted in some convenient large vessel, placed in another one containing water to which the heat is applied; meanwhile the larger tank is filled about half full of water, and this is heated by Bunsen burners placed under the tank. Before the water has reached its boiling point the burners are taken away or turned down very low, then the smaller tank is placed in the larger one and the melted paraffin is filtered into it through some clean piece of cloth, preferably linen. The smaller tank is filled to such a depth with paraffin that, when one of the dipping boards is lowered all the way down into it, the paraffin will rise nearly to the top of the tank but not run over. Now one of the dipping boards is flushed with water under a faucet, and when this has been allowed to drain off until the water falls by drops, the board is quickly pushed down into the paraffin and as quickly withdrawn, being held at one end by both hands. This will result in a thin layer of paraffin quickly cooling all over the two sides of the board, and if the conditions are just right very little paraffin will drip from it. When after about a minute the surface of the paraffin has become firm, cold water is again flushed all over the board, but only for a very short time. This makes the paraffin layer so firm that the board can be hung from a hook and the paraffin peeled off in two layers. These sheets, about 25 by 52 cms., are piled up one on top of the other on flat board, just as they are peeled off the dipping board, and can usually be left in that way for a day or two in a moderately cool room, since the water still on the sheets

will prevent them from sticking to each other. As soon as the two sheets have been removed from the board and laid away, the dipping board is again flushed with cold water and the process is repeated.

The reason for having the dipping boards bevelled sharp at the side and bottom edges is that this causes a break in the paraffin layer there, and so allows the two sheets to be peeled off separately. The reason for having more than one dipping board is that one is liable to give poor results; for the paraffin may begin to stick to its surface, and when it once starts to do so, the trouble is hard to correct in any other way than by letting the board get dry once more and vigorously sandpapering the troublesome place. Using two or three boards, one may pick out after trial the one which gives the best sheets.

By varying the conditions somewhat, one may obtain smooth paraffin sheets of almost any thinness desired. They are very easily, and perhaps most conveniently, made about half a millimeter thick. If the water bath is made hotter, the sheets of paraffin will turn out thinner, until finally there comes a time when the paraffin film will split and full-size sheets cannot be obtained. Another means of controlling results is found in the temperature of the wet dipping board. The warmer it is allowed to become the thinner will be the sheets. With a little practice and judgment one can get sheets of good, smooth surface. A good deal depends on keeping the surface of the melted paraffin in the smaller tank free from air bubbles. Usually the sheets obtained will be thinner near the top end of the dipping board and thicker near the lower end, but this makes little difference if one cuts condenser sheets out of the middle portion.

About two hundred good sheets were made by the writer in a few hours one afternoon, of the grade of paraffin melting at 47°.5. The water adhering to these sheets was allowed to evaporate over night by laying the paraffin sheets singly on large sheets of rough paper, such as is used for mimeograph work. The water in evaporating is likely to leave a conducting film over the paraffin, and moreover there are some slight unevennesses in the surfaces of sheets. It was found that the thin blades of steel used in the Gillette safety razor were admirably adapted for use in lightly scraping the paraffin, and in this way the conducting films were removed and very smooth sheets resulted. For this operation, and in fact to be handled at all, the paraffin should be kept in a room at a temperature of about 23° or 25°. The sheets are then sufficiently yielding and plastic, so that they may be scraped without danger of cracking.

When a sheet had been thus scraped smooth, it was immediately used to build up the condenser. A smoothly scraped surface of a sheet

would be placed on a tinfoil sheet, and then the other surface scraped down somewhat, this process serving to press the paraffin into close

Observations on March 25, 1908.

TABLE XLV.

"PURE PAR. P" *vs.* AIR.

Volts.	Throw.	Charging Time.	Temp.
136	2.30	0.0017	
136	"	"	(cold)
136	2.49	0.00007	
	After	10 A. M.	
131	4.29	0.00007	
"	"	"	
"	4.39	0.0017	
"	"	"	
"	4.38	"	25°.0
"	"	0.00007	
"	4.47	0.00005	
"	4.43	"	
"	4.39	0.0017	
"	4.17	30 secs.	
126	4.22	" "	
131	4.42	0.0017	25°.2
"	4.40	0.00007	

contact with the tinfoil. Then another sheet of tinfoil would be placed on top and pressed down smoothly by a small plate of soft rubber, and the process continued as before. The paraffin sheets were 20.5 cms. by 31.0 cms., and a margin of about 1.5 cms. was left outside the tinfoil sheets. About 18 or 20 dielectric sheets of paraffin sufficed to give a

capacity approximately equal to that of the air condenser. These sheets were placed on a wooden base of the same size, but nothing was put on top, and no pressure was applied. The tinfoil ends were, as usual, soldered together with low melting point solder and were furnished with copper wire terminals. Finally the edges of the pile of paraffin sheets were melted together, and melted paraffin was run all over the tinfoil ends so as to insulate the whole from the air.

Three such condensers were built up. The first one was made with great care, only the most perfect sheets being used for it. The other two were not so carefully prepared and their sheets were considerably thinner. The first one, "Pure Par. P," showed no leakage current whatever under 520 volts on the d'Arsonval galvanometer, while the other two leaked very slightly. But the most pleasing observation was that each of these three condensers showed almost no residual charge formation. In fact, in the region of small charging intervals, where the mica condensers still show a considerable residual forming current, none whatever could be observed in the three pure paraffin condensers. Nor do the throws obtained for the shortest charging time bear any evidence of a probable increase of residual forming current for still shorter charging times.

The observations taken are shown in Table XLV (520 volts across charged condenser and d'Arsonval give no deflection).

It will be seen from these figures of Table XLV that no certain evidence for a measurable residual charge exists, in the region of charging times up to .0017 second. With the combination of condensers here used the ballistic throws for the shortest charging intervals should, if

Observations on March 27, 1908.

TABLE XLVI.

"Pure Par. Q" *vs.* Air.

Volts.	Throw.	Charging Time.	Temp.
133	−7.32	0.0017 sec.	
"	(−7.61, −0.25, −0.06)	2 min.	
132.5	(−7.62, −0.28, −0.05)	" "	20°.0
132	(−7.30, −0)	0.0017 sec.	
"	−7.30	0.00007 sec.	

there were any considerable residual charge, be larger than for those with 0.0017 second of charge, and this relation is found in scarcely more than half the cases. On the other hand, there is a continual increase of the throws, due probably to a temperature influence. Of course any effects due to a temperature-coefficient of capacity will be highly magnified in measuring differential throws, as is done here.

In the last three measurements, recorded above and in all the following ones, the 50 microfarad condenser was connected across the storage battery.

TABLE XLVII.

"Pure Par. R" *vs.* Air.

Volts.	Throw.	Charging Time.	Temp.
132	−4.37, −0	0.00007 sec.	
"	−4.39, −0	0.0017 sec.	
"	(−4.61, −0.10, −0.01)	2 min.	
131.5	(−4.60, −0.16, −0.01)	" "	
"	−4.32	0.00007 sec.	20°.0
"	−4.31	0.0017 sec.	
"	(−4.57, −0.15, −0.01)	2 min.	

TABLE XLVIII.

"Pure Par. P" *vs.* Air.

Volts.	Throw.	Charging Time.	Temp.
131	−3.59	0.00007 sec.	
"	(−3.87, −0.19, −0.06)	2 min.	20°.0
"	−3.60	0.0017 sec.	

TABLE XLIX.

TESTS FOR LEAKAGE THROUGH CONDENSER.

Condenser.	Capacity.	Volts.	Deflection.	Current in amp.
P	0.0448	518	0	0
Q	0.0468	"	0.03	0.33×10^{-8}
R	0.0452	"	0.10	1.10 "
Air	0.0428	510	0.13	1.43 "

From these results we derive —

TABLE L.

RESIDUAL CHARGE FORMATION IN PURE PARAFFIN.

Condenser.	Time of Charge.	Percentage Residual.
P	2 min.	$y + 0.67$
Q	" "	$y + 0.69$
R	" "	$y + 0.50$

EXPLANATION OF THE CURRENT CURVES.

(Figures 2–9, 11.)

We have thus found experimentally a number of values of the residual charge which is formed in various charging times in various condensers. To get a rough but fairly correct insight into the behavior of a condenser during the short charging intervals which have been used, we may proceed as follows: Taking the experimental results in the form of the residual charge, as expressed in percentage of "free charge," we find the increments of residual charge corresponding to the increments of charging time. We measure off the various charging times used in the experiment as abscissas, on any convenient scale. Then we divide all the residual charge increments by their corresponding

charging time increments, thus getting several quotients. Straight lines are now drawn parallel to the axis of charging times, of length equal to the various charging increments and at distances from the axis which are proportional to the quotients obtained for the corresponding time-increments, and finally the ends of these straight lines are joined by lines parallel to the ordinate axis. No line is drawn above the time-interval 0–0.00007 second, since the amount of residual charge formed in this interval is unknown, being represented by y per cent of the "free charge."

After having thus constructed a broken curve for a certain test condenser, we see that the area under each horizontal part of the broken curve represents the residual charge which was formed in the time interval corresponding to this part. Furthermore, the distance of any horizontal line from the time-axis, or the ordinate of this line, will represent the strength of the *average* residual forming current which flowed into the condenser during the corresponding time interval. If we had accurately determined the residual charges formed for a very large number of charging times, spaced closely together on the time-axis, the broken curve, constructed as just described, would give an extremely close approximation to the actual residual forming current. As we have data for only three or four charging increments, our broken curves are necessarily very rough; nevertheless, they give us a correct idea of the general behavior of the current and its high value near the instant of beginning a charge.

The curves of residual current (Figures 2, 5–11) have been constructed as just described. In Figure 2 curves are given of both residual charge and residual forming current. A centimeter of abscissa represents 0.01 second of charging.[3] A centimeter of ordinate means for the charge curve a residual charge of 1 per cent of the "free charge" of the condenser, and for the current curve a residual forming current which in one second would charge the condenser with a residual charge equal to its "free charge." Accordingly a square centimeter of area under the broken curve is equivalent to 1 per cent of "free charge." All the other figures which show these broken line residual forming currents are on the scale of 1 cm. abscissa for 0.0001 second of charging and 1 cm. ordinate for a residual forming current which would give a residual charge of ten times the "free charge," if it continued to flow uniformly for 1 second after the charging begins. Thus, a square centimeter of area under these curves represents one tenth of one per cent of the "free charge" of the condenser.

[3] These dimensions have been changed in reproduction, but the square corresponding to 1 or 0.1 per cent of free charge is given with each figure.

Several of the current curves, if plotted out for each interval of the charging time, would show a depression such as has been shown in the case of the cover glass condenser (Figure 12). It is barely possible that this peculiar result may be genuine and indicate a "backward surge" of the extra dielectric polarization which is conditioned by the molecules of the dielectric. But it is more likely that it is due to experimental error in the estimation of the charging time and perhaps in the reading of the ballistic throws. The peculiarity occurs sometimes in the charging interval corresponding to the second thickness of the type metal strip and sometimes in that of the third thickness. In either case the experiment is extremely delicate and one would expect a slight shifting to occur.

Conclusion.

The results of this research, as shown graphically in the "current curves of the Figures," prove clearly that the current which forms residual charge, or, in other words, the "absorption current," is far from negligible when the charging interval is very small. Not only is the current very large, but the residual charge which it forms within 0.0017 of a second after charging begins, is of the order of several per cent of the "free charge." Glass and paraffined paper condensers show the greatest residual charge formation for short charging times. In each of the two mica condensers which were tested the residual charge which is formed in 0.0017 seconds is only one-half of 1 per cent of the "free charge." But, on the other hand, the mica condensers exhibit an absorption current which decreases but slowly with the time, so that for long-continued charging they may take up much more residual charge than the paraffined paper condensers, whose absorption current is very large at first but decreases much more rapidly as the time increases. The glass condenser shows both a high residual forming current immediately after the beginning of the charge and a rather slow decrease as the time increases. To give a striking example of its high initial value, we may note that during the charging interval from 0.00007 to 0.00020 seconds its average value is such that if it continued uniformly for one second, the condenser would get a total residual charge equal to one hundred times the total "free charge."

It thus appears that the conception of "free charge" is not a very convenient one, for various investigators have shown that the law of superposition holds true, at least to a very close approximation, and this law gives the corollary that if a condenser has been charged for a long time with a constant potential difference and is then discharged,

the residual charge will be liberated at precisely the rate which characterized the residual forming current on its entrance into the condenser during the long-continued charge. No experiments have been made in the present work in which the rate of liberation of residual charge was observed, but the law, if closely tested, will probably be found verified fairly well, and, if this is so, we may conclude that the so-called "free charge" of condensers such as glass and paraffined paper contains an appreciable quantity of very mobile residual charge.

Many investigators have noticed that the capacities of most condensers vary considerably with the frequency of the alternating current, when determined by one of the bridge methods, the capacities invariably decreasing as the frequency is increased to high values. Now if the results of the present research can be applied to chargings by means of an alternating electromotive force, and we see no reason why they should not apply, then it follows that the variation in the capacity of a condenser is not primarily due to the increased frequency, or decreased period, but to the decreased charging interval, or time of contact of the vibrating tongue with the condenser terminal. In fact, it seems that the measured capacity should *increase* with increasing frequency of alternation, provided the contact time of the vibrating tongue is made longer at the same time. Of course this condition can be realized for a certain range of frequency only.

The fact that a considerable part of the residual charge is very mobile is well illustrated by some observations on one of the condensers made of pure paraffin sheets. As shown by the results tabulated above, no satisfactory evidence was obtained of a measureable quantity of residual charge formed in such condensers within 0.0017 of a second after the beginning of charging. When this condenser was charged for two minutes, it was found to have formed 0.7 per cent of residual charge, as measured by the air condenser neutralization method, in which no residual charge is lost. But when the same condenser had been charged for many minutes and then discharged by momentary short circuit, only 0.1 per cent of residual charge was obtained, all the rest having apparently disappeared along with the main discharge. Yet this momentary short circuit forms an essential feature of the experiments carried out by many investigators, who have studied, by means of the quadrant electrometer, the reappearance of residual charge after a momentary short circuit.

As to the cause of residual charge, the results of the work cannot give much information. It seems likely, however, that air bubbles in the dielectric medium play a very important rôle in absorption of charge. I hope to be able to carry on further investigations with even

shorter charging intervals, and I should not be at all surprised if by these means the "free charge capacity" of a good condenser of paraffined paper sheets without the air bubbles could be decreased considerably toward the capacity of a condenser of like dimensions using pure paraffin.

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